THE INFLUENCE OF DÉBRIS ON THE FLOW OF GLACIERS.

THE behavior of ice under various conditions is frequently illustrated by experiments with pitch or other similar viscous fluids or plastic solids. If sand or other similar substance is distributed through pitch its plasticity will be reduced. When sufficient sand is added, the pitch will no longer flow under conditions that will cause clear pitch to readily change its shape. The reason for this is manifest; by mingling a rigid substance with one that is plastic the rigidity of the latter will be increased. As the percentage of rigid material increases the compound substance acquires more and more of its characteristics. Let us apply this principle to glaciers.

Ice under pressure behaves as a plastic solid. When a mass of ice, unsupported at the sides, is sufficiently large, it will change its shape of flow under the influence of its own weight. Although objections have been raised to each of these propositions, I shall for the present consider them demonstrated.

The study of glaciers, especially of the Alpine type, has shown that they flow after the manner of plastic solids. That is, there is a differential motion of molecules, or of particles, throughout the mass. In most instances, it seems safe to assume no two points, in a cross section of a glacier, will move at the same rate for any considerable time.

If we conceive of a glacier composed of clear ice moving at a given rate, and introduce débris—earth, sand, stones, bowlders, etc.—into it, without altering other conditions, the effect will be to decrease the rate of flow, since rigid substances are added to one that is plastic. If we gradually increase the percentage of débris, the ice becomes less and less plastic and finally acquires such rigidity that under the conditions normally influencing the movements of glaciers, it will cease to flow. If the débris instead of being uniformly commingled with the ice, is introduced irreg-

ularly, local changes in the rate of flow, and even local stagnation may be produced.

Stating this principle in the form of a proposition we have: The rate of flow of glacier ice, under given conditions, will depend on the percentage of débris commingled with it, and be least when the percentage is greatest. The nature of the débris, whether coarse or fine, smooth or angular, etc., will modify the result, but this need not be considered at present.

I shall attempt to indicate briefly the bearings of this principle in explaining certain glacial phenomena. What follows, however, is of the nature of suggestions to glacialists, rather than an effort to discuss the various problems touched upon.

Glacial erosion and subglacial deposition.—In the upper portion of a mountain valley that has been occupied by a glacier, as for example, Bloody Cañon, California,[1] the grade is frequently steep and the rocks intensely glaciated and but lightly covered with débris; lower down in the same valley, the grade decreases, and the bottom is deeply filled with débris that was deposited beneath the former glacier. In such an instance, the rate of flow of the former glacier was greatest in the upper portions of its courses and decreased down stream. In the upper portions also, the percentage of débris in the basal layer of ice was least and increased toward the extremity of the glacier. The swifter current and light change of débris in the upper portion of the glacier would favor erosion; while farther down its course a decrease in the rate flow, especially of the basal portion, would result both from loss of grade and also because of an increase in the percentage of contained débris. The débris-charged ice in contact with the rocks would be retarded and when the percentage of foreign material in it became sufficient would cease to flow. The heavily charged and stagnant bottom layer would increase in thickness as more débris was brought from up the valley or descended through crevasses and moulins in the ice. When the ice finally melted the débris accumulated in its basal portion would be left as a ground moraine.

The increase in rate of flow, in the instance above cited, from

[1] Eighth Ann. Rep. U. S. Geol. Surv. 1886–7, pp. 337–340.

the densely charged bottom layer to the clearer ice vertically above, might be gradual or abrupt, according as the percentage of débris decreased gradually upwards or had a sharply defined upper limit. When the change was abrupt, a plane of shear might be established. Whether a glacier charged at its base with débris, shall erode or deposit at a given locality depends on its rate of flow. The rate of flow is controlled by several factors, one of the most important being the percentage of débris contained in the ice. If the débris-charged ice in contact with the rocks beneath moves at all it will cause abrasion; if so heavily charged with débris, however, that it is rigid under the forces to which it is subjected, it will remain stationary and not only cease to erode but protect the rocks beneath, and lead to the accumulation of débris. A glacier may, therefore, erode in one portion of its course and in another portion accumulate débris in its stagnant bottom layer. Also, a decrease in the rate of flow may cause débris-charged ice to stagnate at a locality where erosion was previously in progress; while an increase in the rate of flow might lead to the removal of a previously stagnant layer.

If a glacier occupies a valley in which there is a change from a precipitous to a gentle slope, the rate of flow on the precipitous slope, other conditions being the same, will be greater than below, and may be sufficient to carry forward an amount of débris which would cause stagnation when the more gentle slope was reached. A glacier might, then, erode the rocks over which it passed in one portion of its course and farther on, accumulate débris in its basal portion so as to cause stagnation, without an increase in the amount of foreign material carried. Whether a glacier shall erode or deposit, depends, therefore, on a ratio between strength of current and the percentage of débris in its basal portion.

Clear ice in flowing over ordinary rocks has but slight if any power to abrade them. If débris of the kind commonly present in glaciers, is added to the ice, other conditions remaining the same, its erosive power will be increased until the percentage of débris is sufficient to materially check the flow, and will then decrease as

motion becomes less and less, and finally cease when stagnation results. The conditions most favorable for abrasion seem to be when the bottom layer of a glacier is lightly charged with small, hard and angular rock fragments. Other factors than those just mentioned, however, influence the abrasive power of glaciers; as, for example, the pressure with which the débris is held against the rocks over which it is moved. In the middle course of a glacier, pressure is normally greater than near its extremity, where active waste is in progress; greater abrasion might, therefore, be expected to occur in its middle course than near its extremity. The firmness with which débris is held in its icy matrix, also influences it action as an abrading tool. It is reasonable to suppose that in a névé region the stones in contact with the rocks beneath, would be held less securely than in the compact ice of a glacier proper. This may be one reason why the upper portions of formerly névé-filled amphitheaters are frequently without smoothed and striated surfaces. Weathering in such situations, however, is more active than in lower regions; which may, perhaps, account sufficiently in many instances for the absence of ice abrasion referred to.

Unconsolidated deposits beneath glaciers.—In the well-known instance of Muir glacier, the ice, at its extremity, rests on unconsolidated gravel. That the gravel well beneath the ice, however, in this and other similar instances, is really unconsolidated may be questioned. It is more reasonable, perhaps, to assume that such subglacial gravel is bound together by ice, and really forms a part of the glacier that rests upon it, but owing to excess of rocky material remains stagnant and allows the less highly débris-charged ice above to flow over it. Although this may be the explanation of the conditions now presented, in the example referred to, it does not explain how the ice first advanced upon the gravel.

The gravel beneath Muir glacier was deposited by streams, in an unconsolidated condition, previous to the advance of the ice upon it, and differs both in character and in the manner of its accumulation from a ground moraine.

A glacier advances, as has been shown by Professor Reid,

owing to the more rapid flow of the surface portion, which carries it over and beyond the ice previously forming the terminus. The more rapid flow of the surface as compared with the basal portion, is, no doubt, due, as commonly stated, to an increase in friction toward the bottom. The basal portion generally, however, contains more englacial débris than the superior portion and for this reason would also be retarded. As fresh ice is carried beyond the extremity of a glacier, it is more and more exposed to conditions which favor melting and thus, if the ice contains débris, tends to increase the percentage of foreign material in the portion that remains unmelted. The ice thus advanced, in its turn, becomes basal and is buried as the ice from above continues to descend.

Even in the case of a glacier composed of clear ice, advancing in the manner just cited, upon an unconsolidated gravel bed, the basement layer would become charged with gravel as a result of the contact and thus caused to stagnate. The ice at the bottom being densely charged with débris might remain stationary until melted and thus protect the gravel below from the erosive action of the ice flowing over it.

Terminal moraines.—In the case of an ice stream which contains englacial débris, the increase in the rate of melting toward its extremity will, as already stated, cause an increase in the percentage of débris in the portion that remains unmelted. As the melting of a glacier is mainly superficial, a concentration of englacial débris is brought about by the débris first becoming superglacial and then falling into crevasses and other openings. As the percentage of débris increases in the wasting extremity, the flow of the ice is retarded, and stagnation finally results. Usually, also, in the case of Alpine glaciers, there is a gradual decrease in volume and also in gradient toward their extremities, which again leads to a decrease in their rate of flow and favors stagnation. The presence of a large percentage of englacial débris in the extremity of a glacier, however, will cause stagnation under conditions that would allow a clear ice-stream to flow on. A dam of débris-charged ice is thus formed which will check the advances of clearer ice from above, and cause it to increase in

thickness and expand. The effects of such a check will vary with conditions.

In the case of a growing glacier, the increasing volume of ice above the dam, would cause it to rise and flow over the obstruction, which would then become subglacial. If the glacier was slowly wasting away, its terminus might remain stationary for a time and increase in thickness and then continue to diminish, leaving its highly débris-charged extremity to slowly waste away and finally leave a terminal moraine. The delicate balancing between conditions which cause a glacier to advance, and those favoring recession, so frequently to be observed, would lead to many variations in the changes induced by the congestion of débris, above considered. This process will be again referred to in connection with the influence of débris on fluctuations in the lengths of ice streams.

It is frequently stated that terminal moraines are formed by the carrying forward of superglacial débris and its projection over the end of a glacier. Ridges of débris may frequently be seen about the extremities of glaciers, which are receiving additions in this manner. Such ridges usually have smooth outer slopes and when the ice withdraws from them, the sides left unsupported, acquire even slopes, also, owing to the sliding down of the material; their crest lines are sharp, but frequently undulating in the direction of their length. Terminal moraines of this character are in reality aprons of débris, analogous to talus slopes at the bases of steep cliffs.

Moraines of another type illustrated by the great terminal which crosses New Jersey, Pennsylvania, etc., have broad, hummocky surfaces, with basins between, and originate from the melting of débris-charged ice. Their irregularities in relief are due to the unequal melting of the ice that held the débris, and the concentrations of the foreign material in depressions after it became superglacial, in the manner now well shown in the broad moraine-covered border of Malaspina glacier. Irregularitie would also result from inequalities in the distribution of the débris while yet englacial.

Two types of lateral moraines, corresponding in the manner

of their accumulation, with the two varieties of terminals just cited, may also be recognized.

The influence of débris on the behavior of glaciers that advance upon a plain and build morainal embankments, like those at the mouth of Bloody Cañon, California, might be traced, but space forbids such an extension of this paper.

Variations of glaciers.—Much attention is now being directed to fluctuations in the lengths of glaciers. As is well known, many Alpine glaciers alternately advance and retreat in the course of a few years, or remain stationary for a term of years and then undergo marked variations. These changes are usually considered to be due directly to variations in meteorological conditions. Glaciers in the same group, however, which, so far as one can judge, are exposed to the same climatic changes, frequently fluctuate differently. One glacier may be advancing, while its neighbor, perhaps draining the same névé field, is retreating. What has been stated above, however, in connection with the stagnation of the extremities of glaciers, when congested with débris, suggests that fluctuations in their lengths may be due to other causes than climatic changes.

Advances and retreats of the end of a glacier may evidently result from (1) variations in the rate at which snow is accumulated on its névé, (2) to changes in its rate of melting, and (3) to fluctuations in its mean rate of flow.

1. Variations in the accumulation of snow on the névé of a glacier may be considered as causing pulsation, or "waves," which would progress throughout its length and on reaching its extremity cause an advance or retreat. How an increase or decrease in the rate of accumulation on a névé would affect a glacier flowing from it, can, at present, only be conjectured. But it is reasonable to suppose that a moderate "wave" produced in this manner would become less and less well defined the greater the extent of the glacier it traversed, and its final effect on the length of the glacier be inappreciable. Marked changes in the volume of a névé would, however, unquestionably affect the glacier flowing from it and cause variations in its length. The opposite changes exhibited in

neighboring glaciers may also be explained in this way. For example, two glaciers subjected to the same climatic influences, but of unequal length, or if of the same length but of different mean velocity, would advance at different times in response to the same impulse, for the reason that the time required for a "wave" to reach their extremities would be different.

The effects of variations in névé regions on the length of the glaciers flowing from them, have recently been discussed by Professor Reid in this JOURNAL[1] and need not be considered further at present.

2. Variation in the rate at which glaciers melt, might be considered as a factor in studying the halts, advances and retreats observed at their extremities; but meteorological observation in Alpine valleys and the behavior of the ice streams entering the same valleys, do not show an intimate connection.

3. The rate of flow of glacier ice is influenced, as already stated, by the percentage of débris mingled with it. The increase in the percentage of débris near the end of a glacier, may as we have seen, cause it to become stagnant and form a dam of débris-charged ice. When this occurs the terminus of the glacier will become stationary. If the current from above is sufficient to cause the ice to rise, and flow over the obstruction, an advance of the terminus will result. When the energy of the glacier is feeble, it may be held in check for a while, perhaps adding to the height of the débris-charged ice that retains it, and then retreat. The withdrawal of a glacier from its stagnated extremity is perhaps a more varied process than an advance beyond it. The extremity of a glacier that has been checked in the manner here considered, will be covered with superglacial débris. The effect of a surface covering on the wasting ice is varied. As is well known, a small amount of débris, especially if dark colored, will promote melting; while a larger amount will shield the ice beneath and assist in its preservation. For this reason, the abundantly débris-covered extremity of a glacier will waste more slowly than the less thoroughly covered portion farther up stream. In the case of a slowly retreating glacier

[1] Vol. III., 1895, pp. 278–288.

this may cause the clear ice above a débris-charged ice-dam to melt away, and form a new terminus which would in turn become congested and undergo a similar process once more.

An explanation is, then, suggested of the varying behavior exhibited by the extremities of glaciers, which is independent of fluctuation of climate. Two glaciers supplied in their névé regions with the same amount of snow, and alike in all respects except in the percentage of débris carried by them, would have the débris concentrated in their extremities at different rates and hence form débris-charged ice-dams at different periods, and consequently be checked and advance or retreat at different times and at different intervals. If in the case of two glaciers the amount of débris carried was the same, but other conditions varied, the fluctuation of their extremities would again vary. So diverse are the conditions controlling the flow of glaciers, that in no two instances could their fluctuations in length, due to the influence of débris, be expected to occur synchronously.[1]

Drumlins.—In the case of a mass of englacial débris, densest at its center and gradually becoming less and less abundant in all directions, it is evident that glacial motion will be least at its center and increase in all directions until the normal flow of clear ice under the conditions present will be reached. If the central portion of such a mass is sufficiently charged with débris, glacial flow will there cease and the stagnant portion be carried along, for a time at least, as englacial bowlders are carried. If such a stagnant nucleus should be situated at the base of a glacier, however, it would retain its position and the clearer ice above and on either side would flow past it. The "plucking" of débris from such a stagnant mass might lead to its removal, but if the advancing ice contained rock fragments, these on coming

[1] The considerations offered above, lead to the suggestion that a series of terminal moraines in a formerly glaciated valley, or a similar succession of ridges left by a continental glacier, are not necessarily evidence of repeated climatic oscillations, but may have been formed during a uniform and continuous meteorological change favorable to glacial recession. That is, a débris-charged glacier may retreat for a time, then halt, and again retreat, owing to its terminus becoming congested with foreign material, in response to a climatic change which would cause a glacier composed of clear ice, to recede continuously and without halts.

in contact with the débris-charged ice, would be retained, and thus add to the accumulation. The stagnant mass would be under pressure, and both by the addition of material and the removal or plucking away of material, would be given a shape which would present least resistance to the ice flowing past it, and its longer axis would be parallel with the direction of ice movement. That is, it would have the form characteristic of *drumlins.*

As already stated, when the ice at the base of a glacier is generally charged with débris, it may form a stagnant layer over which the clearer ice above will flow. On final melting, the débris in such a layer would form a ground moraine. If inequalities existed in the bottom over which the glacier moves, or the supply of englacial débris is not uniform, stagnant débris-charged ice may be concentrated at one locality and erosion occur at the same time at an adjacent locality. The same thread of the ice current may deposit at one time and erode at another time and *vice versa*, according as it loses or gains in percentage of contained débris or its energy is varied by other causes. When the supply of débris carried by an individual portion of a glacier is long continued, elongated mounds and even lengthy ridges may be formed. All phases presented by drumlins from those accumulated about boss of rock, to oval mounds, elongated hills and long narrow ridges, may apparently be accounted for by the behavior of débris-charged ice and variations in the volume or constancy of the supply of englacial material. There seems no good reason why we might not have drumlins formed of gravel, sand or loess, as well as of till.

While the explanations suggested in this paper may not all hold when more thoroughly considered, and when tested by observation and experiment, yet I feel confident that the principle on which they are based is valid and will be found important both in discussing theories of glacial motion, and in explaining the mode of origin of many glacial deposits.

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